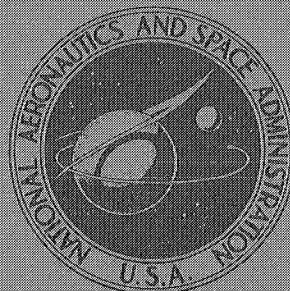


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BASELINE PERFORMANCE OF SOLAR
COLLECTORS FOR NASA LANGLEY
SOLAR BUILDING TEST FACILITY

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BASELINE PERFORMANCE OF SOLAR COLLECTORS FOR NASA LANGLEY SOLAR BUILDING TEST FACILITY

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SUMMARY

The Solar Building Test Facility located at the Langley Research Center in Hampton, Virginia, currently utilizes a 1180-square-meter (12 700-ft²) solar collector field to help heat and cool a 4650-square-meter (50 000-ft²) office building. The solar collector field contains seven collector designs. Before operation in the field, the experimental performances (thermal efficiencies) of the seven collector designs were measured in an indoor solar simulator at the Lewis Research Center in order to provide a baseline for later comparison with actual field test data. The simulator test results are presented for the collectors as received and after several weeks of outdoor exposure with no coolant (dry operation). Six of the seven collector designs tested showed substantial reductions in thermal efficiency after dry operation.

INTRODUCTION

The Solar Building Test Facility (SBTF) project, a joint project of the NASA Lewis Research Center and the NASA Langley Research Center, was conducted to improve the technology for solar heating and cooling of commercial buildings (ref. 1). The SBTF consists of a 4650-square-meter (50 000-ft²) one-story office building that has been modified to accept solar heated water for the operation of its 600-kilowatt (170-ton) absorption air conditioner and its baseboard heating system. A 1180-square-meter (12 700-ft²) solar collector field with seven different collector designs provides the solar heated water, and a 114-cubic-meter (30 000-gal.) tank is used for storage when needed. The facility is located at the Langley Research Center in Hampton, Virginia.

As a part of the Lewis effort, preliminary thermal performances of all seven collectors (as-received, i. e., before outdoor exposure) were obtained in the Lewis indoor solar simulator (described in ref. 2). After these indoor tests, each collector was placed outdoors and exposed to the Sun with no coolant provided (dry operation). The

collectors were then retested in the solar simulator to determine if any performance degradation was caused by dry operation.

The primary purpose of these tests was to provide baseline thermal performances of the SBTF collector designs for subsequent comparison with the collector performance after extended field operation. The secondary purpose of the tests was to determine whether dry exposure would alter the thermal performances of the collectors. This report describes the collectors tested, the baseline test methods used, and the collector thermal performance both before and after dry exposure. In addition, a brief description of the physical damage incurred during dry exposure is presented.

DESCRIPTION OF SBTF SOLAR COLLECTORS

The collector field for the Solar Building Test Facility (fig. 1) consists of 12 rows of collectors. The initial collector mix includes seven collector designs from five collector manufacturers. Pertinent details of the seven collector designs and their distribution in the field are given in table I. The rationale used in collector selection and additional detail on the SBTF are given in reference 1.

Because the collectors had to properly interface with the SBTF collector field, they have several common features: All collectors (1) were hydrostatically tested to 690 kilopascals (100 psig), (2) were capable of withstanding 146 kilograms-per-square-meter (30-lb/ft^2) wind loads and 98-kilogram-per-square-meter (20-lb/ft^2) snow loads, (3) had weatherproofed housings, (4) had pressure drops of less than 2.41 kilopascals (0.35 psi) between the inlet and outlet under the design flow rate of 31.5×10^{-6} cubic meter per second (0.5 gal/min), and (5) were capable of complete drainage while tilted 32° to the local horizon (for emergency freeze protection while installed in the field). Each collector has a copper-constantan thermocouple attached to the absorber plate on its vertical centerline, 0.305 meter (1 ft) from the top of the absorber plate. Further details of the features of each collector design are given in figures 2 to 6, which show the Chamberlain, Sunsource, General Electric, Libbey-Owens-Ford, and Martin-Marietta collectors.

TEST APPARATUS AND PROCEDURE

Indoor Simulator

A picture and a schematic of the solar simulator are presented in figures 7 and 8. The indoor solar simulator is capable of controlling several collector test conditions that cannot be controlled outdoors: wind velocity, solar flux level, and ambient tem-

perature. The fluid flow rate is monitored by a turbine flowmeter and adjusted by means of a 186-watt (1/4 hp) gear pump. The fluid is a 50-50 by weight mixture of ethylene glycol and water. The fluid-inlet temperature is obtained by immersion heaters located in an 0.303-cubic-meter (80-gal) hot water tank in combination with two other heat exchangers upstream of the collector inlet manifold. The additional heat exchangers are used for precise control of the fluid temperature before it enters the collector. Wind velocity is provided by a fan. Solar flux level is attained by the solar simulator with a controllable flux range of 0 to 1105 watts per square meter (0 to 350 Btu/hr·ft²). Ambient temperature or room temperature of the facility is held constant by means of a roof exhaust fan.

The collector is mounted on a stand with an adjustable table that enables variations of collector tilt angles and incident angles of radiation.

The simulator flux level is measured with a water-cooled Gardon radiometer having a sapphire window and was calibrated in accordance with the National Bureau of Standards irradiance standard. Instrument Society of America (ISA) type E thermocouples are used to measure ambient temperature and collector fluid inlet and outlet temperatures. The thermocouples were calibrated at 0 and 100° C (32° and 212° F).

The millivolt-level electrical outputs of the measuring instruments are recorded on magnetic tape by the use of a high-speed data acquisition system. The information from the tape is sent to a digital computer for data reduction and compilation. The computer results are printed out in the test facility within minutes after the data are initially recorded. A more detailed description of the facility can be found in reference 2.

Outdoor (Dry) Test Setup

The temporary setup for dry exposure was simple but functional. It consisted of a wooden framework on which the collectors were mounted and exposed to insolation for several weeks. Figure 9 shows the dry operation setup with three collectors in place. A strip chart recorder was used to record the absorber plate temperatures from the thermocouple on each absorber plate and the insolation measured by a pyranometer located in the plane of the collectors. The collector inlets were open to avoid any pressure buildup during the warming cycles. The accuracy of the absorber-plate temperature measurements was on the order of $\pm 2.3^{\circ}$ C ($\pm 5^{\circ}$ F), whereas the insolation measurement was within ± 1 percent of the full insolation.

Test Procedure

The general test procedure was to determine the efficiencies of the as-received collectors, then subject the collector to an outdoor, dry exposure, and finally determine the efficiencies after dry exposure.

Tests in the indoor simulator involved running the collector at two fluid flow rates, 24.4 and 48.8 kg/m²·hr (5 and 10 lb/hr·ft²), two flux levels, 600 and 880 watts per square meter (190 and 280 Btu/hr ft²), and three inlet temperatures, ambient, 49° C (120° F), and 71° C (160° F).

The collector was mounted on the test stand such that the solar simulator radiant flux was normal to the collector. Before the solar simulator was turned on, the collector was allowed to reach thermal equilibrium at the lower flow rate of 24.4 kg/m²·hr (5 lb/hr·ft²), based on absorber area, and a selected fluid-inlet temperature. It usually took about 1 hour for the warmup. Once thermal equilibrium was established, the simulator was turned on and set for the appropriate flux level by adjusting the lamp voltage. These conditions were then maintained until steady-state conditions were achieved for the collector (about 15 min), whereupon the data were recorded. The radiant flux was then readjusted to a different value at the same inlet temperature, steady-state conditions achieved, and data were again recorded. The flow rate of the collector was then changed to the 48.8 kg/m²·hr (10-lb/hr·ft²) value, and the process repeated. After recording data at the two flows and two fluxes for one inlet temperature, another inlet temperature was then set and the entire process repeated.

After the performance mapping was obtained in the indoor simulator, the collectors were mounted on the outdoor test stand for the dry exposure tests. Each collector was operated several hours at different temperature regimes of 93°, 121°, 132°, and 149° C (200°, 250°, 270°, and 300° F) before finally reaching the maximum temperatures achieved during full exposure. This was accomplished by monitoring the collector temperature, covering the collector when the desired operating temperature regime was reached, allowing some cool down, and then uncovering the collector and repeating the process. The result was a saw-toothed temperature profile as shown in figure 10 where the three Chamberlain collectors shown in figure 9 were simultaneously exposed to the Sun. This method allowed a systematic means of stepping up the temperature (to help determine the temperature at which any damage occurred) before allowing the maximum temperatures achieved during exposure to full insolation. After each temperature level was achieved, the collectors were examined for visible signs of physical damage. Photographs were taken to record the visible damage. The duration of the dry exposure was 3 to 9 weeks.

After dry exposure, the collectors were returned to the simulator, where an efficiency curve at a flow rate of 48.8 kg/m²·hr (10 lb/ft²·hr) was again obtained to determine any change from the as-received data.

RESULTS AND DISCUSSION

Chamberlain Two-Glass Selective Black Paint Collector

Results of the as-received tests on the two-glass, selective black paint collector are shown in figure 11, along with the post-dry-operation results. The collector efficiency is plotted against the ratio of collector-inlet-temperature-minus-ambient-temperature to insolation. The as-received results are given for two flow rates: 48.8 and 24.4 kg/m²·hr (10 and 5 lb/ft²·hr). The post-dry-operation data is shown by the dashed line. All post-dry-operation data were obtained at a flow rate of 48.8 kg/m²·hr (10 lb/hr·ft²).

It is apparent in figure 11 that a significant change in collector efficiency occurred between the as-received and the post-dry-operation conditions. A summary of the dry-operation tests and observations made is given in table II for all collectors tested. The table shows that changes were first noted for this collector at 132° C (270° F).

A photograph showing the visible change that occurred appears in figure 12. A smokey appearing deposit occurred on the inner surfaces of both glazings in a swirl pattern. This pattern, however, abruptly changed at the centerline of the glazing, indicating that the deposition was taking place on a residual material left on or put on the glass during fabrication. This residual material apparently acted as a nuclei for deposition of an unknown material. Discussions with the manufacturer indicate that the foam insulation would outgas at temperatures approaching 132° C (270° F). It is also possible that the selective paint on the absorber plate could have outgassed.

In any event, after the collector was allowed to cycle to higher temperatures, the swirl pattern deposit seemed to disappear, restoring the collector to its original appearance (as shown in fig. 2). Maximum plate temperature measured during these tests was 160° C (320° F). Even though the deposits seemed to disappear, the collector performance was significantly degraded (see fig. 11). The shift in the efficiency curve shown at the ordinate (change of intercept) indicates a change in the optical properties of the collector, that is, glazing transmittance and/or solar absorptance of the absorber plate coating. Since no visible deposition remained, it appears that a change occurred in solar absorptance of the selective paint. The slope of the efficiency curve also changed slightly, indicating a small change in the heat loss characteristics of the collector. Changes in collector heat loss could be brought about by changes in (1) the insulating properties of the insulation, (2) the glazing seals and (3) the thermal emittance of the absorber plate coating. Overall, changes in both the intercept and the slope of the efficiency curve could also be brought about by changes in the heat transferred between the coolant and the absorber plate. This possibility, however, seems remote for the type and duration of exposure (not enough time for buildup of internal deposits in flow channels). Although not conclusive, it appears that the major cause of degradation due to the dry exposure was changes in the optical properties of the selective paint.

Chamberlain One-Glass, Black Chrome Collector

As-received and post-dry-operation test results for the one-glass, black chrome collector are shown in figure 13. Again, the collector thermal efficiency degraded after dry exposure, but the degradation is not as large as that experienced on the two-glass, selective paint collector. Table II shows that deposits started to occur at 132°C (270°F).

Figure 14 shows the deposits after dry exposure and, although the deposits are pronounced, the overall effect on performance is not as significant as one might expect from the physical appearance of the collector. The maximum temperature measured on the absorber plate during the dry exposure was 182°C (360°F). The deposits are suspected to originate from the outgassing of the foam insulation beneath the absorber plate. The deposition appeared to occur rapidly once a threshold temperature was reached, with no noticeable change with increasing exposure time. Subsequent discussions with the manufacturer have confirmed that the deposition most likely resulted from the outgassing of the foam insulation. This deposition in turn degraded the optical properties of the collector, namely, the transmittance of the glazing.

Chamberlain Two-Glass, Black Chrome Collector

As-received and post-dry-operation test results for the two-glass black chrome collector are shown in figure 15. For this particular collector an effort was made to determine the effect of time on the deposition process during the dry operation tests. Accordingly, collector efficiency data are also given for an intermediate time step where the collector had accumulated 2.1 hours at temperatures between 121° and 132°C (250° and 270°F).

As seen in the figure, the difference between the data for the short and long exposure appears to be negligible. This indicates that the deposition process occurred early, resulting in a noticeable degradation in collector efficiency. Figure 16 shows the deposits left on the collector glazing after extended dry exposure. The appearance after the 2.1-hour exposure was about the same. Maximum temperature measured during the dry exposure was about 200°C (390°F).

The data shown indicate a change in both the optical properties (intercept shift) and the heat loss characteristics (slope change). The optical property change probably resulted from a change in the transmittance of the glazing due to the deposits. The reason for the change in heat-loss characteristics is not conclusively known. One possibility is that the extremely high temperatures reached during dry testing ($\sim 200^{\circ}\text{C}$ or $\sim 390^{\circ}\text{F}$) deteriorated the insulating properties of the foam insulation.

Sunsource One-Glass, Black Nickel Collector

As-received and post-dry-operation test results for the one-glass black-nickel collector are shown in figure 17. The figure shows that a significant change in collector thermal efficiency occurred after dry operation, despite little or no visible change in the collector appearance (table II). The maximum temperature measured during these dry-operation tests was 166°C (330°F).

The changes in both the ordinate intercept and the slope of the efficiency curve indicate degradation of the optical properties of the coating and/or the glazing and a change in the collector heat loss, respectively. Because no visual change in the transmittance occurred, it is assumed that the absorptance of the black nickel surface degraded. The reason for the change in slope is not understood because it indicates lower heat loss rates for the collector. One possible explanation might be that either the glazing seals or the fiberglass insulating properties improved with the high temperatures encountered during dry testing (i. e., 166°C (330°F)).

General Electric Two-Lexan, Alcoa Selective Surface Collector

As-received and post-dry-operation test results for the two Lexan, selective surface collector are given in figure 18. As can be seen, a significant change in collector thermal efficiency occurred after exposure to dry-operation. The maximum temperature measured during dry operation was 166°C (330°F).

The exact nature of the change is not known; however, this collector contains foam insulation (as noted in table I). Possibly, outgassing could have caused the degradation. It should be noted, though, that no visible change in the transmittance of the glazing was evident. The only anomaly noted was that the Lexan would distort considerably during high-temperature operation, but it appeared to take on its original appearance once the temperatures were lowered. The change noted in figure 18 indicates a possible change in optical properties of the absorber surface and/or the Lexan. Since visible changes in the transmittance were not detected, it is assumed that the absorptance of the selective surface degraded.

Libbey-Owens-Ford Two-Glass, Black Paint Collector

As-received and post-dry-operation test results for the two-glass, black paint collector are shown in figure 19. As can be seen, some differences in collector thermal efficiency occurred during dry exposure. This accompanied some obvious physical damage. Figure 20 demonstrates the damage that occurred during dry exposure. The high

temperatures (e.g., 149°C (300°F)) absorber plate temperature) caused the outer glass to warp and also quickly destroyed the seal between the aluminum collector housing and the glass. The ineffective seal then allowed rain or moisture to collect within the insulation under the absorber plate. After redetermining collector efficiency, the collector was disassembled for inspection. The insulation was water-soaked. The slope change for the post-dry-operation data in figure 19 tends to confirm the degradation of the insulation by water soaking. The shift at the ordinate, however, also denotes some change in optical properties. There was some evidence of a slight deposition along the periphery of the glazing, although it is not visible in the photograph of figure 20.

It was felt that the water-soaked insulation could cause condensation on the collector glazing as well as lower the thermal efficiency during actual field operations. However, the manufacturer has since corrected this problem on the collectors installed in the SBTF collector field by adding new seals and a containment frame for the glazing.

Martin - Marietta Two Glass, Optical Black Collector

As-received and post-dry-operation test results for the Martin-Marietta collector are shown in figure 21. Little difference in collector efficiency occurred after dry exposure. The maximum temperature measured during dry operation was 157°C (315°F).

Summary of Collector Thermal Performance

A summary of efficiency curves for all the collectors used in the SBTF solar collector field is given in figure 22. The flow rate is $48.8\text{ kg/m}^2\cdot\text{hr}$ ($10\text{ lb/hr}\cdot\text{ft}^2$). Also shown in the figure is the minimum thermal efficiency requirement originally specified by NASA for the purpose of collector procurement. All collectors easily exceeded this minimum performance requirement in the as-received condition.

For the SBTF operation relatively hot water ($\sim 90^{\circ}\text{C}$, or 190°F) is needed to drive an absorption air conditioner. Hence, high efficiency was desired, especially at values of the abscissa above $0.053\text{ }^{\circ}\text{C}\cdot\text{m}^2/\text{W}$ ($0.3\text{ }^{\circ}\text{F}\cdot\text{hr}\cdot\text{ft}^2/\text{Btu}$). The relative positions of the collectors in this figure, however, should not be used as the only basis of comparison. A proper comparison should involve not only collector performance, but total system performance and total system costs.

For completeness, a summary of efficiency curves is also given for the post-dry-operation results. This is shown in figure 23 also for a flow rate of $48.8\text{ kg/m}^2\cdot\text{hr}$ ($10\text{ lb/hr}\cdot\text{ft}^2$). This type of curve may be more representative of what can be expected for collector field operation over an extended period of time since it may turn out to be impossible to avoid dry exposure of the collectors during construction, operation, and the

planned and unplanned shutdowns of the field for maintenance. Even with the degradation measured, however, all collectors met or exceeded the minimum thermal efficiency specification.

CONCLUDING REMARKS

The collector thermal efficiency data presented provide a basis for later comparison of the SBTF collectors after extended field use. These as-received collector curves show how the collectors performed before any outdoor exposure. The post-dry-operation performance shows the changes incurred after significant dry exposure to the outdoors; that is, full exposure to the Sun with no coolant. These dry conditions, may well be encountered in the field (unplanned shut-downs or equipment failure), so the post-dry-operation data may be more representative of how the collectors will actually perform after extended use in the SBTF solar collector field.

It is significant to note that six of the seven collector designs tested showed measurable decrease in thermal efficiency after dry exposures of 3 to 9 weeks. This indicates that design improvements are needed to allow dry operation of the collectors without significant degradation. It also indicates that solar system designers should consider using collector efficiency data for collectors that have been exposed to dry operation, rather than data corresponding to new, day-one characteristics.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 3, 1977,
776-22.

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1. Knoll, Richard H.; Miao, David; Hamlet, Irvin L.; and Jensen, Ronald N.: Initial Operation of a Solar Heating and Cooling System in a Full-Scale Solar Building Test Facility. NASA TM X-73519, 1976.
2. Simon, Frederick F.: Flat-Plate Solar-Collector Performance Evaluation with a Solar Simulator as a Basis for Collector Selection and Performance Prediction. NASA TM X-71793, 1975.

TABLE I. - DETAILS OF SETF SOLAR COLLECTORS

Manufacturer	Glazing	Absorber surface	Absorber material and construction	Effective absorber area ^a		Nominal size of collector		Insulation	Number of rows in field	Area	
				m ²	ft ²	cm	in.			m ²	ft ²
Chamberlain	2 Glasses	Selective paint	Steel plates spot and seam welded	2.03	21.9	243.8 by 91.4	96 by 36	5.08 cm (2 in.) Urethane foam	3	311	3348
Chamberlain	1 Glass	Black chrome	Steel plates spot and seam welded	2.03	21.9	243.8 by 91.4	96 by 36	5.08 cm (2 in.) Urethane foam	2	207.4	2232
Chamberlain	2 Glasses	Black chrome	Steel plates spot and seam welded	2.03	21.9	243.8 by 91.4	96 by 36	5.08 cm (2 in.) Urethane foam	3	311	3348
Sunsource	1 Glass	Black nickel	Steel tubes mechanically bonded between two steel sheets	1.39	14.95	185.4 by 96.5	73 by 38	7.62 cm (3 in.) Fiberglass	1	58.3	628
General Electric	2 Lexan	Alcoa selective paint	Aluminum roll bond	2.15	23.1	243.8 by 96.5	96 by 38	2.54 cm (1 in.) Fiberglass board plus 6.35 cm (2.5 in.) Urethane foam	1	109.4	1178
Libbey-Owens-Ford	2 Glasses	Black paint	Aluminum roll bond	1.63	17.56	193.0 by 86.4	76 by 34	7.62 cm (3 in.) Fiberglass board	1	83.2	896
Martin-Marietta	2 Glasses	Optical black surface	Aluminum roll bond	1.97	21.25	243.8 by 91.4	96 by 36	8.89 cm (3.5 in.) Vermiculite	1	100.7	1094

^a Absorber plate area minus any shadowing due to collector frame (e.g., midglazing supports).

TABLE II. - HISTORY OF DRY OPERATION OF SBTf COLLECTORS

Collector	Dry operation		Duration, day	Temperatures at which visual changes occurred		Nature of change	Efficiency degradation after dry exposure
	Maximum temperature, T _{max}			132 ^o C (270 ^o F)	T _{max}		
	^o C	^o F					
Chamberlain, 2 glass, black paint	160	320	19	X		Light deposits on glazing inner surface	Yes
Chamberlain, 1 glass, black chrome	182	360	19	X		Smokey deposits emanating from upper corners of col- lector on inner glazing surfaces	Yes
Chamberlain, 2 glass, black chrome	199	390	32	X			
Sunsource, 1 glass, black nickel	166	330	67	--	--	Unknown	Yes
General Electric, 2 Lexan, Alcoa sel.	166	330	60		X	Distortion of Lexan covers but recovers after cool down	Yes
Libbey-Owens-Ford, 2 glass, black paint	149	300	32		X	Seal failure around glazing due to warping of glazing. Also some deposits around periphery of glazing	Yes
Martin-Marietta, 2 glass, optical black	157	315	32		X	Some distortion in glazing retaining frame but re- covers after cool down	Slight

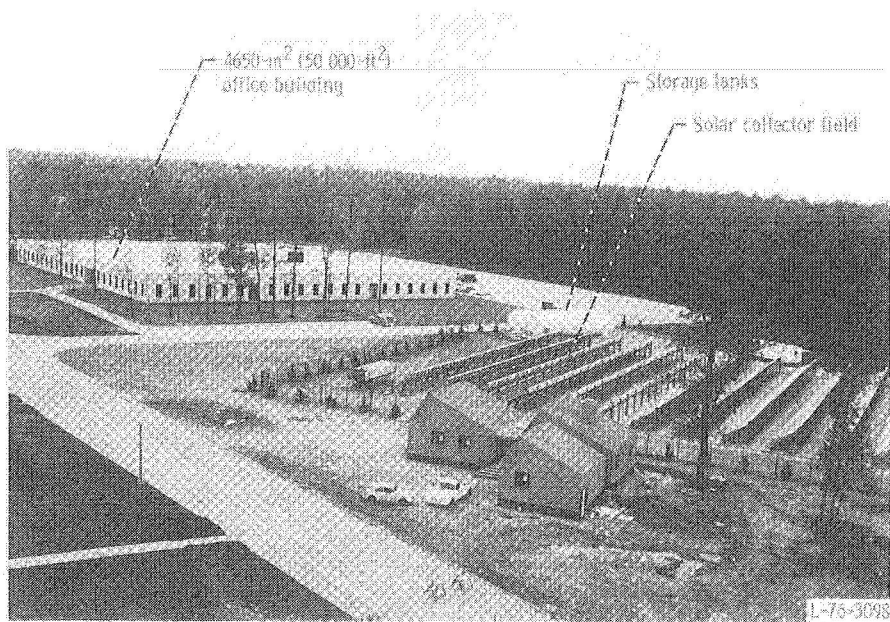


Figure 1. - Solar building test facility.

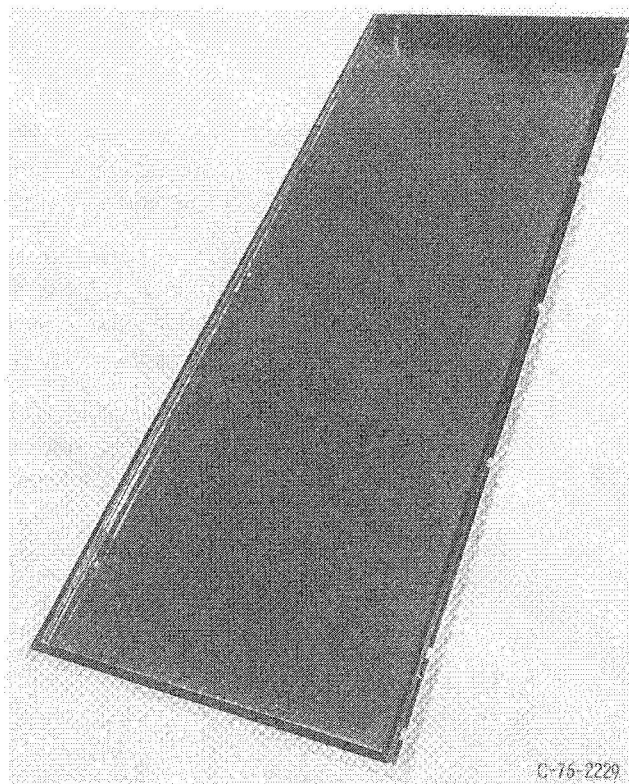


Figure 2. - Chamberlain collector; two glass, selective paint. (Typical of Chamberlain collectors.)

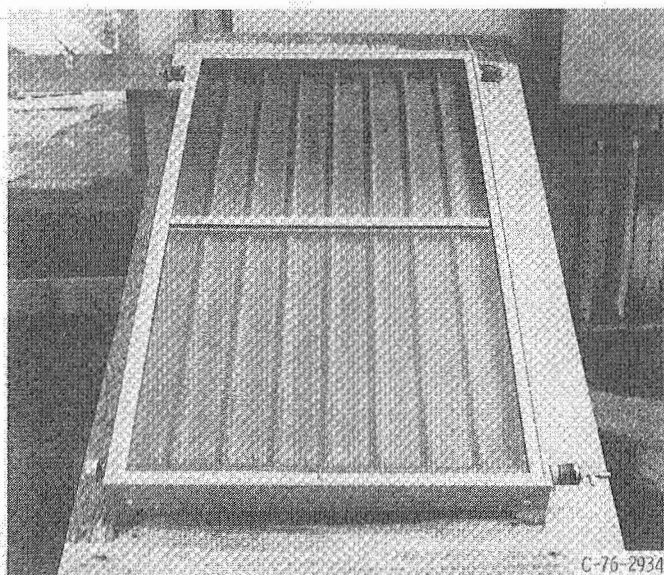


Figure 3. - Sunsource collector.

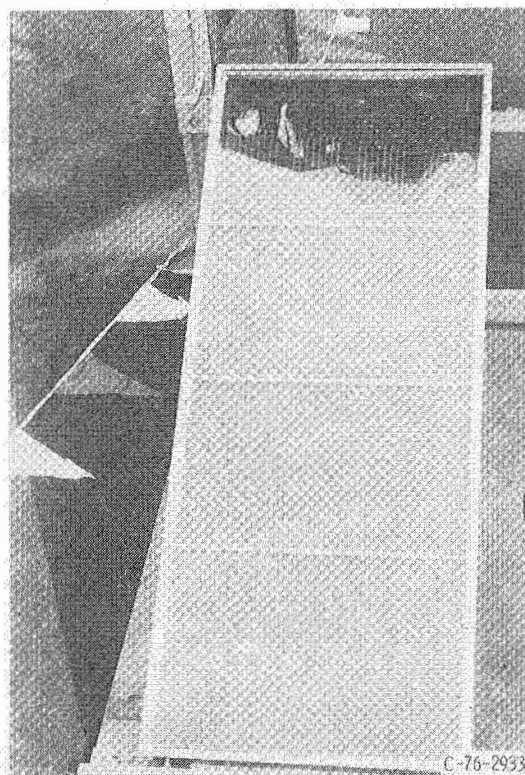


Figure 4. - General Electric collector.

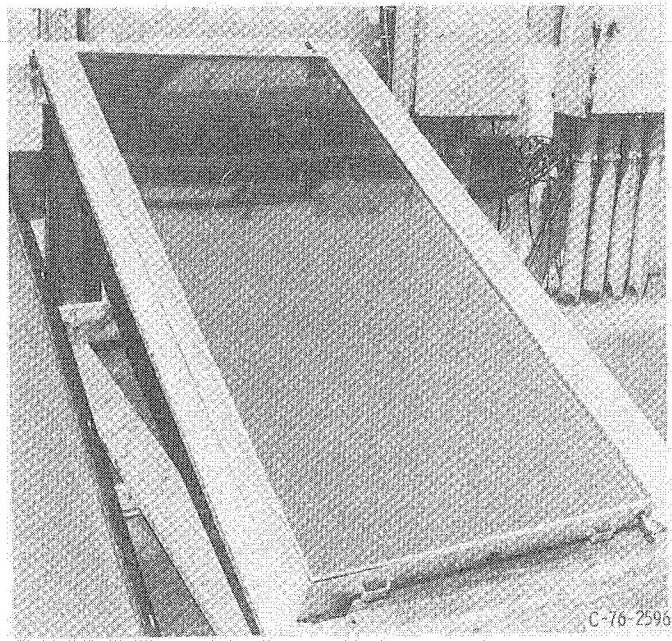


Figure 5. - Libbey-Owens-Ford collector.

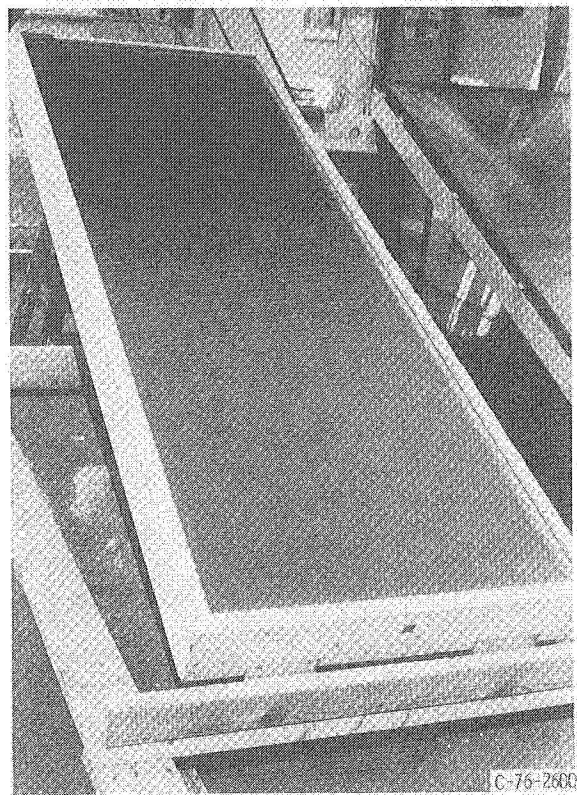


Figure 6. - Martin-Marietta collector.

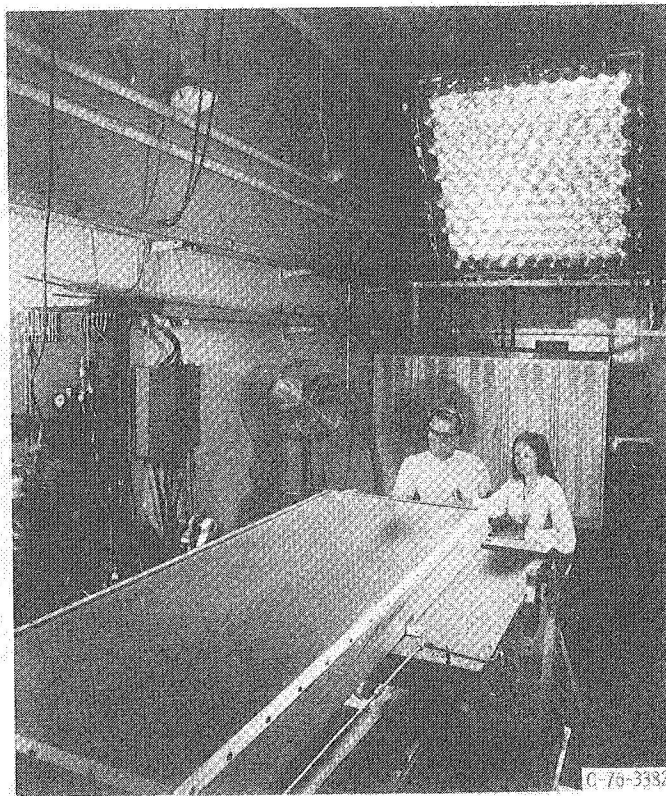


Figure 7. - Indoor facility used to experimentally determine solar collector performance.

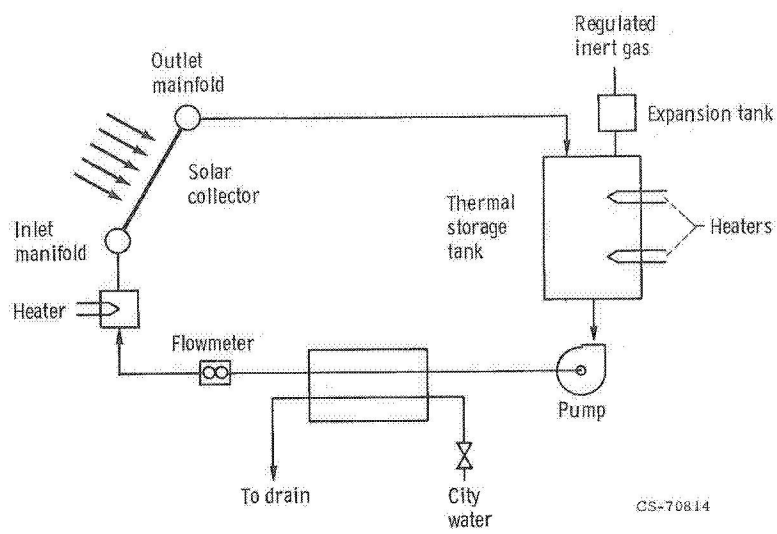


Figure 8. - Schematic of liquid flow loop.

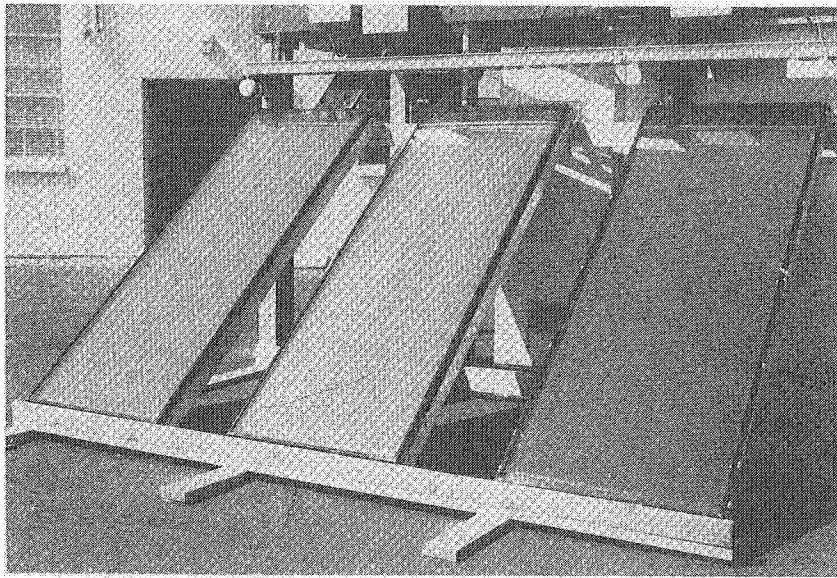


Figure 9. - Collectors mounted on outdoor stand for dry testing (no coolant).

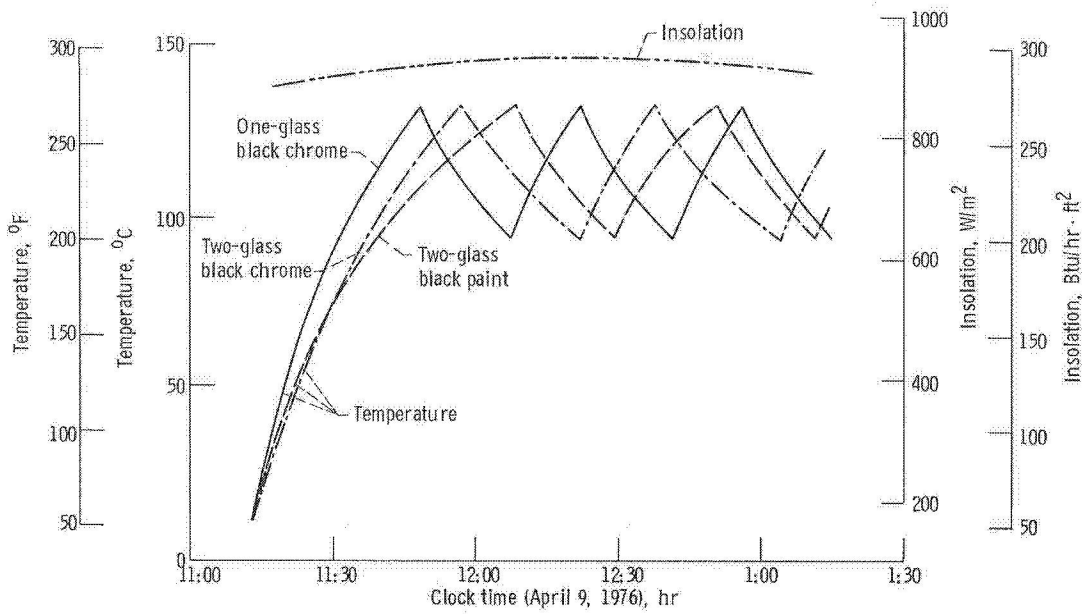


Figure 10. - Cyclic temperature history during initial dry testing of Chamberlain collectors.

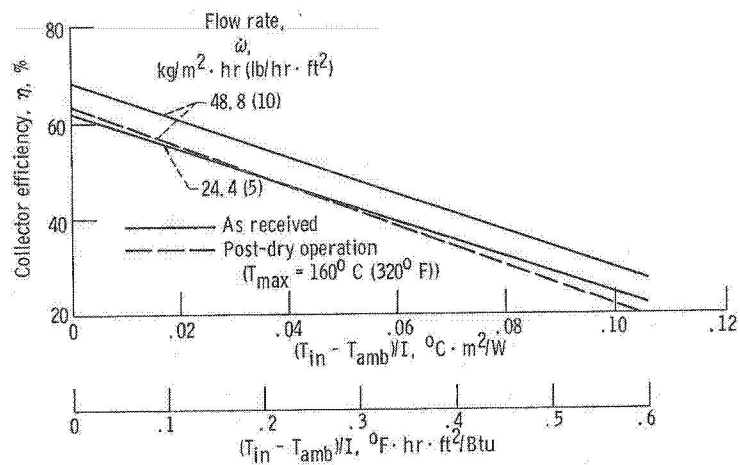


Figure 11. - Measured performance of Chamberlain two-glass, selective paint collector.

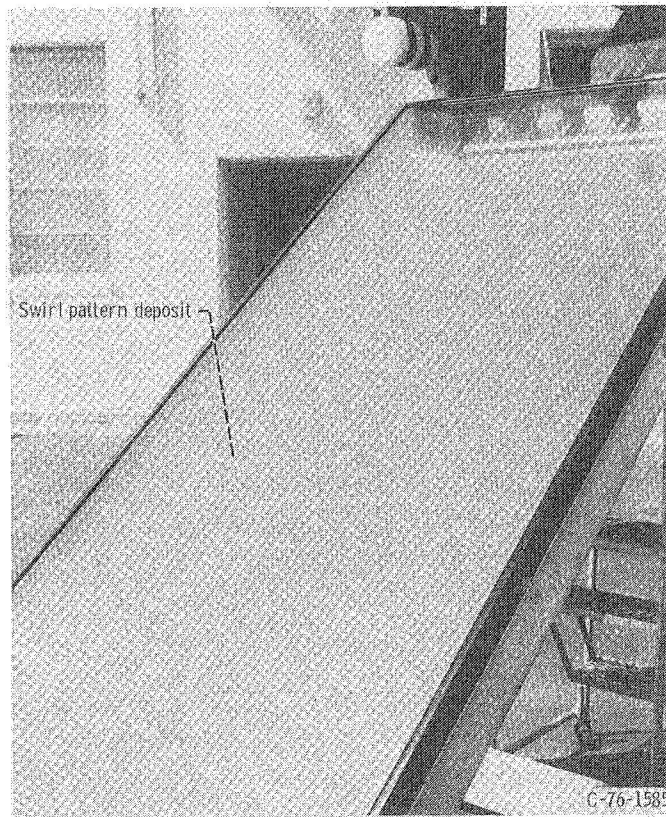


Figure 12. - Early degradation results on Chamberlain two-glass selective-paint collector.

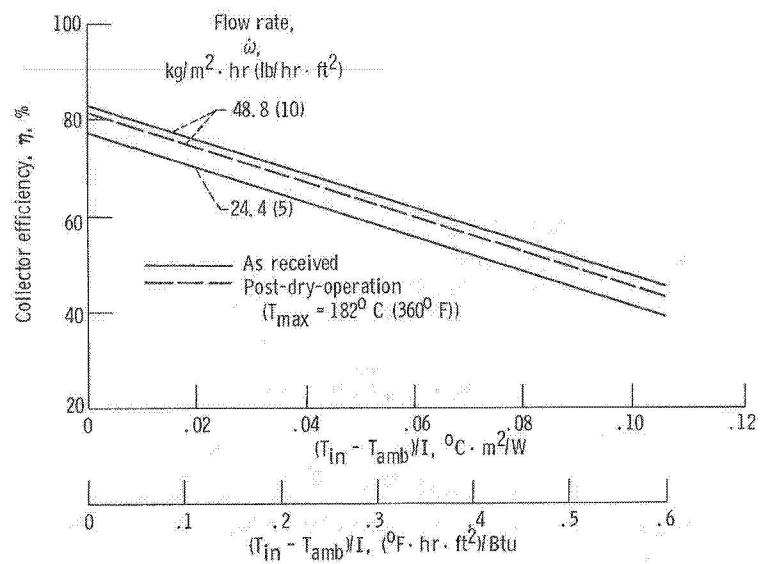


Figure 13. - Measured performance of Chamberlain one-glass, black-chrome collector.

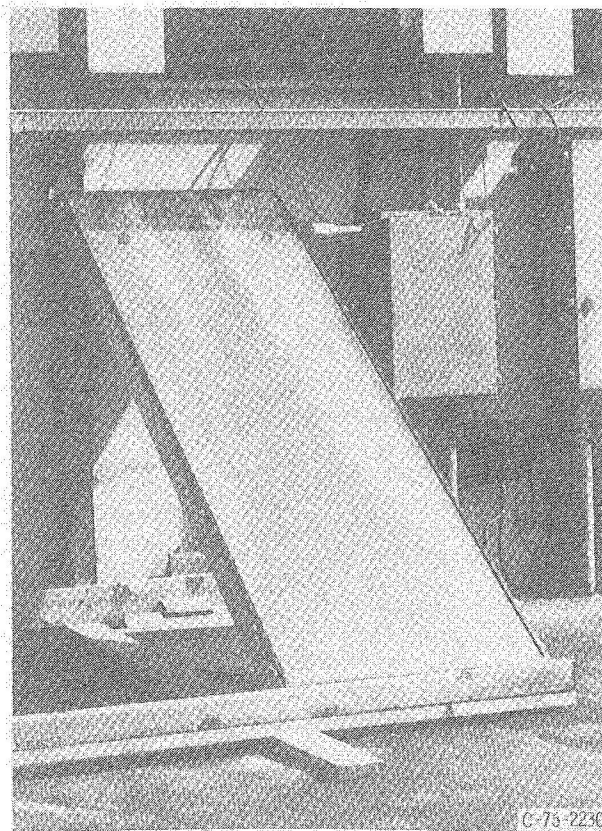


Figure 14. - Outgassing products deposited on glazing of Chamberlain one-glass black chrome collector.

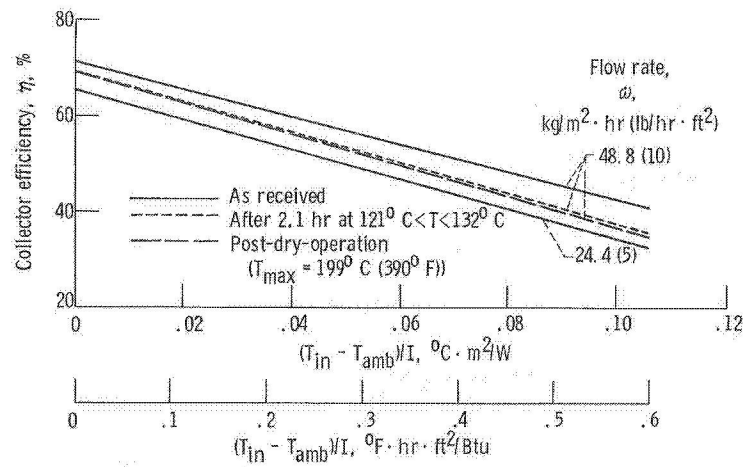


Figure 15. - Measured performance of Chamberlain two-glass, black-chrome collector.

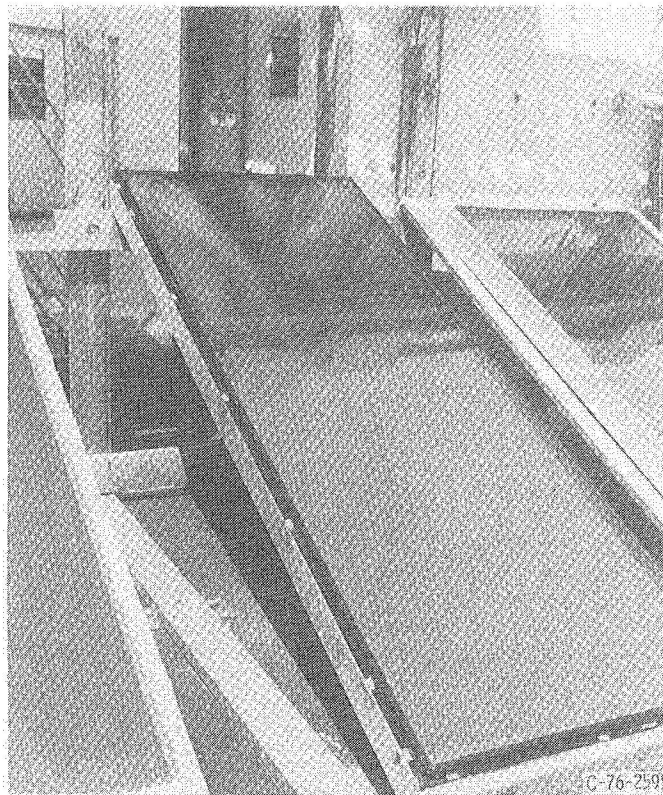


Figure 16. - Outgassing products deposited after extended dry operation of Chamberlain two-glass black-chrome collector.

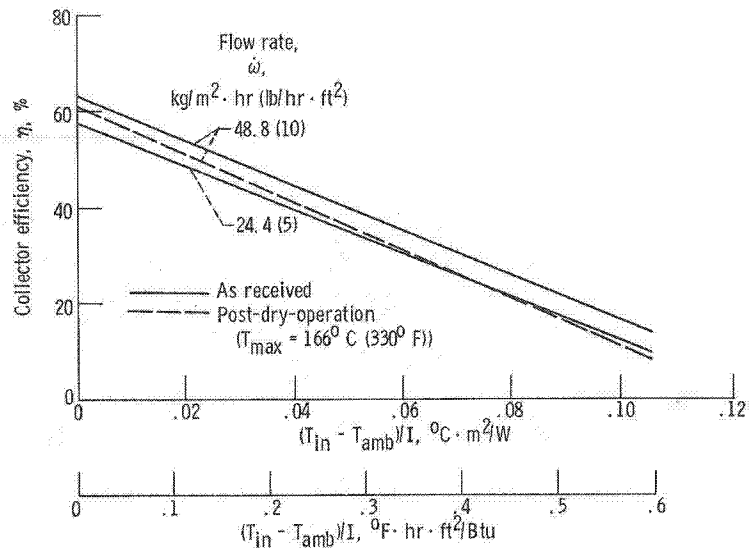


Figure 17. - Measured performance of Sunsource one-glass, black-nickel collector.

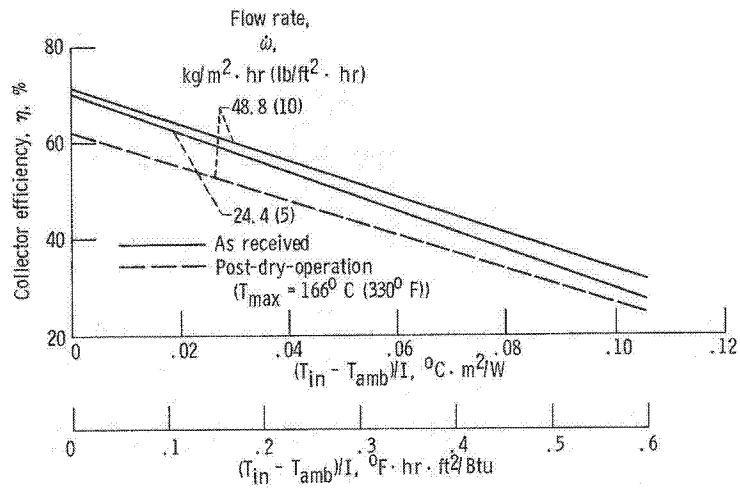


Figure 18. - Measured performance of General Electric two-Lexan, Alcoa selective-surface collector.

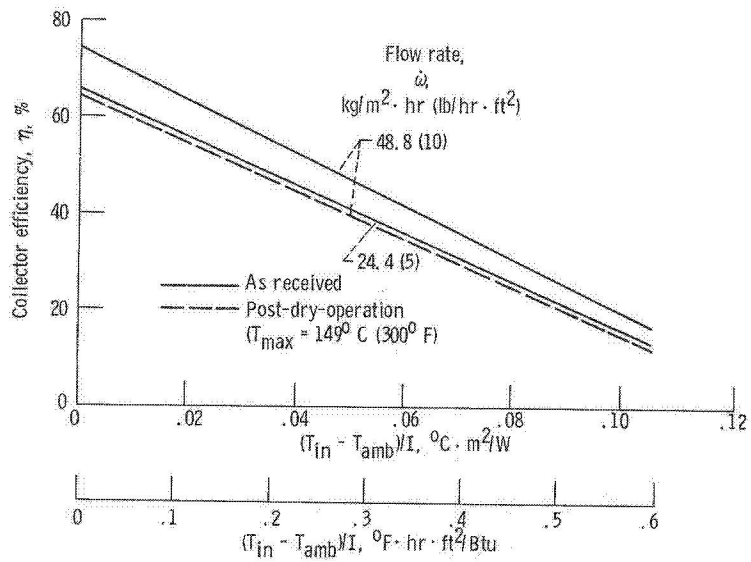


Figure 19. - Measured performance of Libbey-Owens-Ford two-glass, black-paint collector.

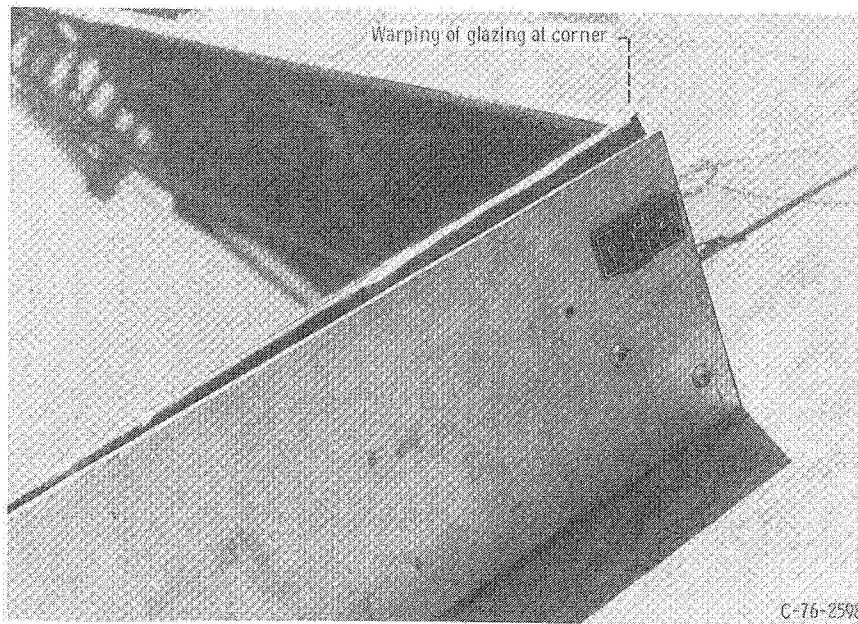


Figure 20. - Libbey-Owens-Ford collector warpage at corners and seal failure after prolonged dry operation.

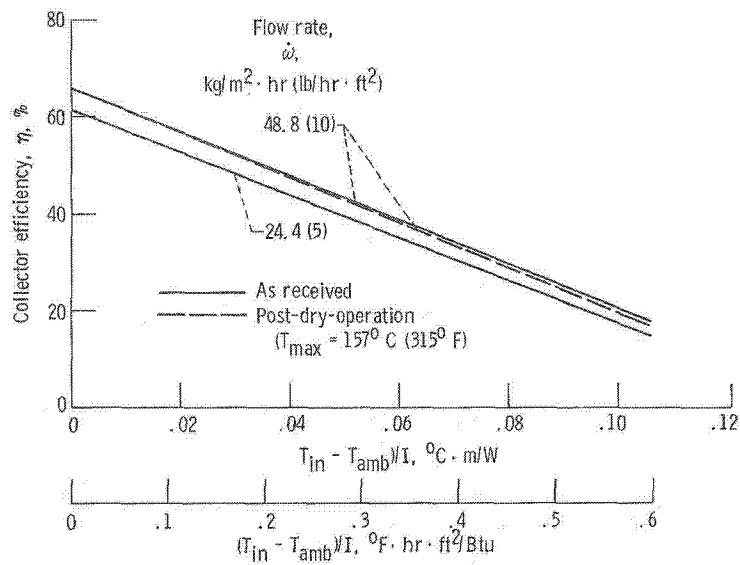


Figure 21. - Measured performance of Martin-Marietta two-glass, optical-black collector.

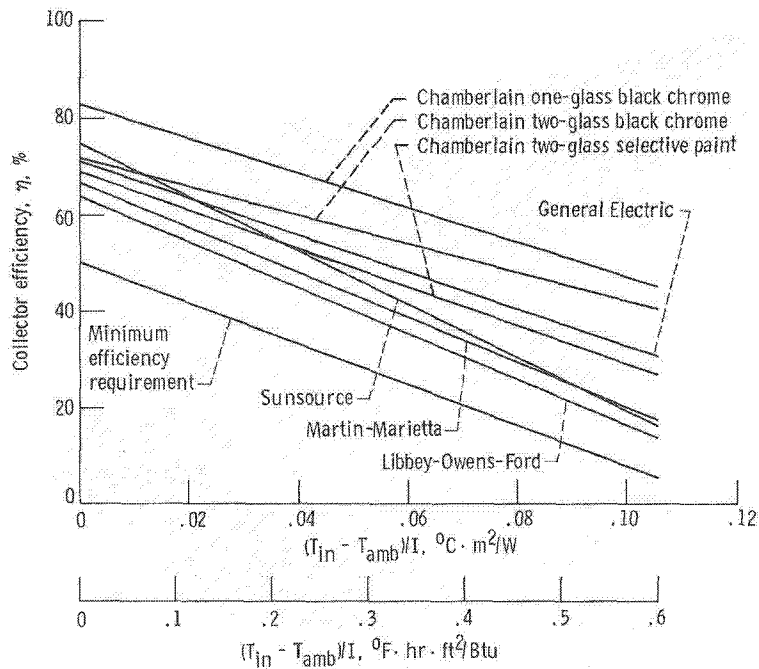


Figure 22. - Summary of as-received performance of collectors. Flow rate, 48.8 $\text{kg/m}^2 \cdot \text{hr}$ (10 $\text{lb/hr} \cdot \text{ft}^2$).

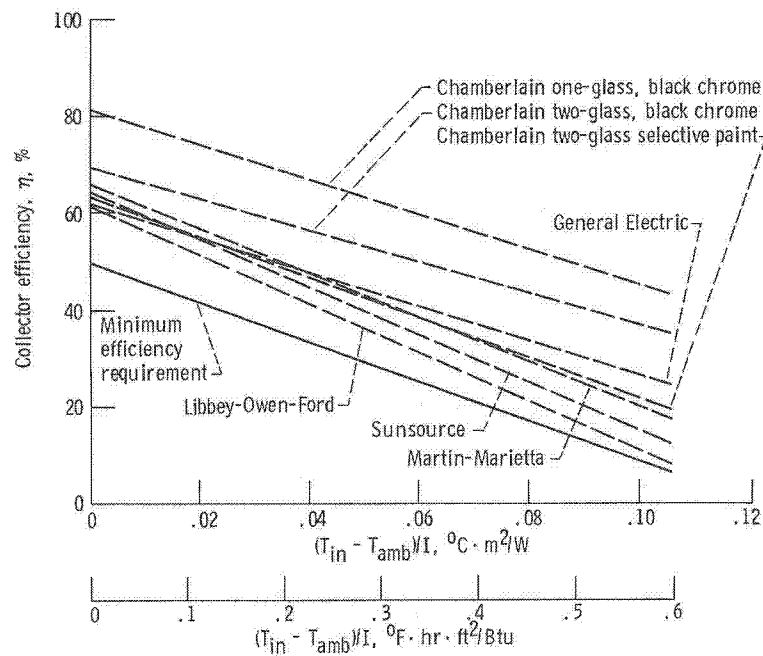


Figure 23. - Summary of post-dry-operation performance of collectors. Flow rate, $48.8 \text{ kg/m}^2 \cdot \text{hr}$ ($10 \text{ lb/hr} \cdot \text{ft}^2$).



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